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Research on Simulation Method of Rigid-Flexible Coupling Gear Transmission Based on MFBD

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Abstract. In order to analyze the dynamics of the gear transmission more efficiently, this paper builds a three-dimensional modeling software Creo, finite element software Hypermesh and dynamics simulation software based on MFBD (Multi-Flexible-Body Dynamics) technology. RecurDyn established a multi-flexible body model, established a rigid-flexible, flexible-flexible gear pair model and verified its accuracy. The time-frequency domain curves and simulation speeds of the vibration accelerations of the two model flexible gears are compared and analyzed. The results show that the rigid-flexible gear pair model has certain advantages in the simulation. The simulation method can provide a basis for rigid-flexible coupling modeling of complex gear transmission systems.

1. Introduction

Gear transmission is the most widely used form of mechanical transmission and is a typical system dynamics problem [1]. Nowadays, the application of multi-rigid body model in system dynamics research is very mature. However, in the practical application of engineering, the system not only has a large range of rigid body motion, but also has its own elastic deformation. In order to analyze more accurately, the use of multiple flexible body models to solve system dynamics problems has become one of the most commonly used methods for researchers.

The gear pair flexible body model includes two kinds of rigid-flexible and flexible-flexible models. According to the theory of flexible multibody dynamics, the number of flexible bodies in the gear transmission system increases, and the simulation results will be closer to the actual motion process, but at the same time it will slow the simulation speed of the model. In order to more efficiently analyze the dynamics of the gear mechanism, a method combining RecurDyn and Hypermesh is constructed in this paper. The rigid-flexible, flexible-flexible gear pair model is established and dynamic simulation is performed. The simulation method is a rigid and flexible gear transmission system. The establishment of a coupling model provides a reference.

2. Multi-Flexible Body Modeling Method

In this paper, the dynamic simulation software RecurDyn based on the relative coordinate system dynamics theory is used. The software uses a complete recursive algorithm to simulate and analyze the dynamics of complex machinery. When dealing with complex and large-scale multi-body system dynamics problems, Its solution speed and efficiency are superior to traditional multi-body dynamics software [2].

2.1 Multibody Dynamics Theory.

The speed of an object in the absolute coordinate system can be expressed as:

$$Y = (Y_0^T, Y_1^T, Y_2^T, ..., Y_{n_c}^T)^T . \tag{1}$$

Where n_c is the number of coordinates in the absolute coordinate system.

The velocity of an object in a relative coordinate system can be expressed as:

$$\dot{q} = (Y_0^T, \dot{q}_{01}^T, \dot{q}_{12}^T, ..., \dot{q}_{(n_r-1)n_r}^T)^T . \quad (2)$$

Where n_r is the number of coordinates in the absolute coordinate system.

Therefore, the Cartesian velocity of all objects can be obtained as follows:

$$Y = B\dot{q} . \quad (3)$$

Among them, coefficient matrix B can be expressed with relative coordinates.

The equation of motion of the system can be obtained from the first type of Lagrangian equation:

$$F = B^T MB\ddot{q} + B^T M\dot{B}\dot{q} + B^T \Phi^T q\lambda - B^T Q = 0 . \quad (4)$$

Where M is the mass matrix; $\ddot{q}$ is the acceleration vector; $\dot{B}$ is the derivative of the coefficient matrix; Φ is the cutter constraint; λ is the Lagrange multiplier; Q is the force vector.

2.2 Multi-Flexible Body Modeling Theory

As shown in Figure 1, the position vector of any point P on the flexible body is:

$$\mathrm{r} = r_0 + A(\mathrm{s}_p + \mathrm{u}_P) . \quad (5)$$

In the formula, r is the vector of the P point in the inertial coordinate system; r_0 is the vector of the origin of the relative coordinate system in the inertial coordinate system; A is the direction cosine matrix; s_p is the P point in the relative coordinate system when the flexible body is not deformed; u_P is the relative deformation vector.

As follows, f can be described using modal coordinates:

$$u_p = \Phi_p q_f . \quad (6)$$

Where Φ_p is the deformation mode matrix and q_f is the generalized coordinate of the deformation.

Therefore, the velocity vector and acceleration vector at any point on the flexible body are:

$$\dot{r}^p = \dot{r}_0 + \dot{A}(\mathrm{s}_p + \mathrm{u}_p) + \mathrm{A}\,\Phi_p \dot{q}_f . \quad (7)$$

$$\ddot{r}^p = \ddot{r}_0 + \ddot{A}(\mathrm{s}_p + \mathrm{u}_p) + 2\dot{A}\Phi_p \dot{q}_f + A\Phi_p \ddot{q}_f . \quad (8)$$

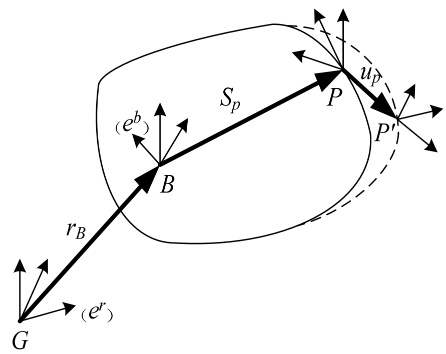


Fig. 1 Flexible body deformation diagram

2.3 Flexible Body Modeling Process.

Flexible body in RecurDyn can be divided into two types: modal flexible body (R-Flex) and finite element flexible body (FFlex) [4]. Modality reduction (R-Flex) adopts modality reduction method, which makes the calculation easy and greatly improves the efficiency of simulation calculation. However, it is inaccurate to model the contact problem. It is necessary to perform finite element analysis through external software first. Renew soft body after deformation mode. The finite element flexible body (FFlex) used in this paper has obvious advantages. In the analysis, the deformation caused by the contact force can be accurately expressed, and the contact between the flexible body and the rigid body and the flexible body can be considered, and the application is more widely used. The built-in finite element program can be directly used for analysis and calculation.

This paper builds a method to establish a multi-flexible gear pair model using three-dimensional modeling software Creo, finite element software Hypermesh and dynamic simulation software Recurdyn. The method flow chart is shown in Figure 2.

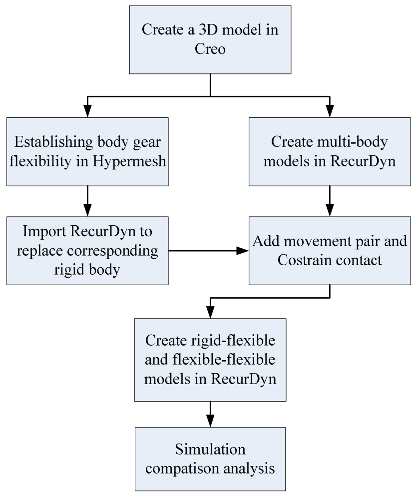


Fig. 2 Multi-flexible body model establishment flow chart

3. Gear Pair Flexibility Modeling

3.1 Pre-processing

Recurdyn's multi-flexible model is achieved by replacing the soft body model with a corresponding rigid body in a multi-rigid body model. The parametric modeling of large and pinion gears was performed in Creo. The basic parameters of the gears are shown in Table 1. Assembly of gears, interference check, and simple kinematics analysis verify the correctness of the assembly.

Table 1 Gear basic parameter

Name	Modulus	Number of teeth	Modification coefficient	Tooth width / (mm)
Large gear	7	27	+0.26	32
Pinion gear	7	31	+0.25	31

The assembled gear pair model is introduced into Recurdyn through the ".x_t" interface file. The rotation pairs between the big and small gears and the earth are respectively set according to the transmission relationship, and the contact force between the two gears is added to complete the establishment of the rigid body model.

The large and pinion gear models are saved in the ".x_t" format and imported into the finite element software Hypermesh [5], and the quality of the grid is checked. Particular attention should be paid to the unit coordination between the software. The grid selects the solid185 unit and sets its material properties. The material properties of the two gears are shown in Table 2 below.

Table 2. Gear Material Property Sheet

Member	Material	Elastic Modulus/ (Gpa)	Poisson's ratio	Density/ (kg.m^{-3})
Large gear	12CrNi4A	2.07	0.29	7880
Pinion gear	20Cr2Ni4A	2.11	0.31	7840

Create a rigid connection point in the center of rotation of the gear and use this node to establish a rigid connection with the surrounding nodes [6]. In the "Export solver deck", select the corresponding "*cdb" file to create the flexible gear body model with the same process as described above.

3.2 Model Import

The established flexible gear body model is introduced into Recurdyn to replace the pinion in the rigid body model. After importing, it is necessary to add motion pairs and contacts to the model:

(1) Select the rotary joint between the rigid connection point of the pinion flexible body and the earth;

(2) Define the tooth surfaces of the bull gear and the pinion with the "patch" element. Select the "Surface to Fsurface" soft body contact in FFlex to establish the contact between the two gears. Establish a good rigid-soft gear pair model as shown in Fig. 4 shows.

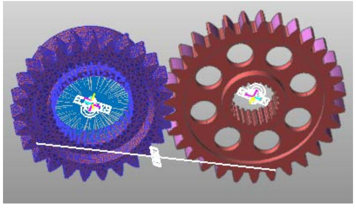


Fig. 4 Rigid-flexible gear model

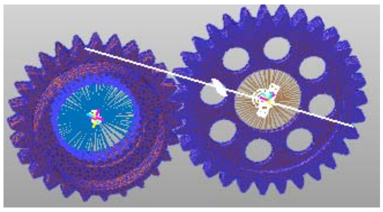


Fig. 5 Flexible-flexible gear model

After the large gear flexible body model is introduced into the above-mentioned rigid-flexible gear pair model, the pair of movements is added and the "Fsurface to Fsurface" contact between the two gears is established, and the flexible-flexible gear pair model is shown in Fig. 5

3.3 Contact Force Parameter Settings

In the multi-body dynamics simulation software RecueDyn, the contact stiffness coefficient, damping coefficient and other parameters need to be set before the simulation, and the contact force formula is [7]:

$$f_n = k\delta^{m1} + c\frac{\dot{\delta}}{|\dot{\delta}|}|\dot{\delta}|^{m2}\delta^{m3}. \tag{9}$$

Where k is the contact stiffness coefficient; c is the damping coefficient; m1, m2, m3 are the stiffness index, the damping index, and the permeability index, respectively, δ is the penetration depth, and $\dot{\delta}$ is the derivative of penetration depth versus time.

The formula for calculating the contact stiffness between two gears is:

$$K = \frac{4}{3}\sqrt{R}E. \tag{10}$$

$$\frac{1}{R} = \frac{1}{R_1} \pm \frac{1}{R_2}. \tag{11}$$

$$\frac{1}{E} = \frac{1-u_1^2}{E_1} + \frac{1-u_2^2}{E_2}. \tag{12}$$

In the formula: R_1 and R_2 are the equivalent radius at the meshing point of two gears; E_1 and E_2 are the elastic moduli of the two gears respectively; u_1 and u_2 are the Poisson's ratios of the gear materials respectively.

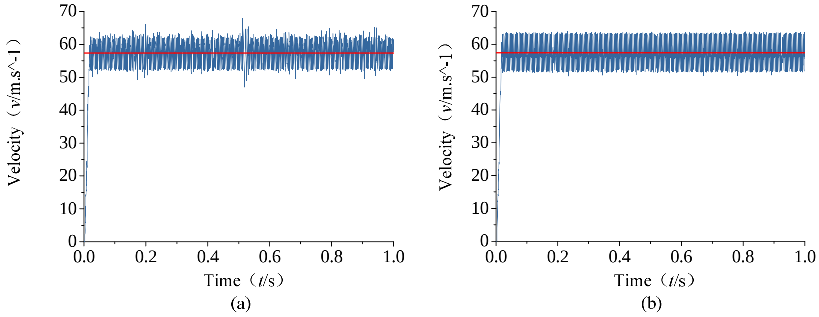
Through the calculation and analysis, the contact stiffness between the two gears is $1145045\mathrm{N/mm}^{3/2}$, the damping coefficient is $50\mathrm{N/(s\cdot mm)}$, and the maximum penetration depth is $0.1\mathrm{mm}$.

4. Analysis of Simulation Results

4.1 Model Accuracy Verification

The accurate model is the basis of simulation analysis. Set the simulation parameters, add the drive speed at the large gear rotation pair, and add a constant torque load to the pinion rotation pair. In order to prevent abrupt changes in the load and rotation speed at the initial stage of the simulation, the STEP function is used to define the speed and load respectively. The gear speed function is step (time, 0, 0, 0.02, 50) and the pinion load function is step (time, 0, 0, 0.02, 200000). After the setup is complete, the simulation is run. The simulation time is 1s and the number of steps is 2000.

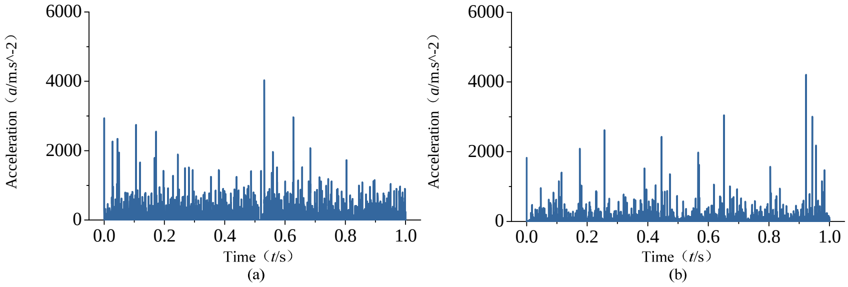
Figure 6 shows the change of the pinion speed in the rigid-flexible and flexible-flexible model. The analysis shows that the speed of the pinion has small fluctuations above and below the calculated value $57.4\mathrm{rad/s}$, and the fluctuation of the pinion speed in the soft-soft model is smoother than the rigid-flexible model, which is consistent with the theory and shows that the model has certain accuracy.



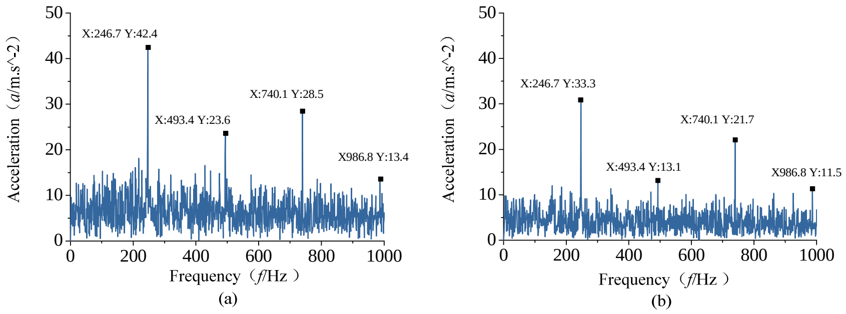
(a) Rigid-flexible model (b) Flexible-flexible model
Fig. 6 Pinion speed change curve

4.2 Vibration Acceleration Simulation Analysis

Vibration acceleration is one of the indicators commonly used in the analysis of vibration characteristics. It can express the speed of the vibration speed change in the time domain, and can express the distribution of vibration energy with frequency in the frequency domain. Figure 7 and Figure 8 are the acceleration time domain comparison diagram and spectrum comparison diagram of the two models.



(a) Rigid-flexible model (b) Flexible-flexible model
Fig. 7 Pinion acceleration time domain comparison chart



(a) Rigid-flexible model (b) Flexible-flexible model
Fig.8 Pinion acceleration spectrum comparison chart

(1) It can be seen in the time domain that the overall acceleration of the rigid-flexible model is greater than that of the flexible-flexible model, and there are certain vibration shocks.

(2) In the frequency domain, it can be seen that the characteristic frequencies of the two models are all obvious. Both the main frequency and frequency multiplication exist in the curves, which are in accordance with the calculated values, and the sidebands are symmetrical about the main frequency. Among them, in the rigid-flexible model, the main frequency amplitude is more obvious than the flexible-flexible model, and the fluctuation is also larger.

In summary, both the rigid-flexible model and the flexible-flexible model can reflect the variation law of the vibration acceleration in the gear meshing process. The characteristic frequency can be obtained through frequency domain analysis.

4.3 Simulation Speed Comparison

The simulation speed of the model is related to factors such as computer configuration, parameter settings, and the number of flexible bodies. This section compares the simulation time of rigid-flexible and soft-soft models to illustrate how fast the model simulates. According to the principle of control variables, the parameters in the two models are set the same and the same computer is used for simulation. When the simulation setting time is 0.25s, 0.50s, 0.75s, and 1.00s, respectively, the simulation time comparison chart is shown in Figure 9.

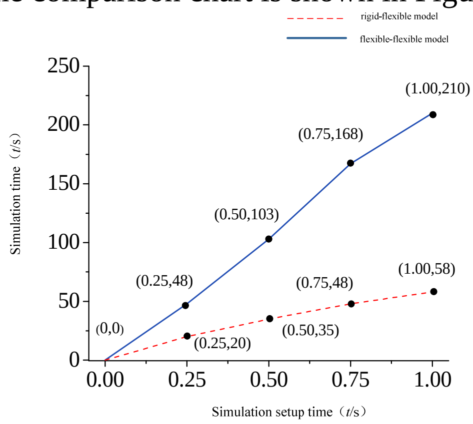


Fig.9 Simulation time comparison chart

As can be seen from the figure, the rigid-flexible model simulation takes much less time than the soft-soft model. According to the calculation of the sampling points, the time of the rigid-flexible model simulation is 27.6%~41.7% of the soft-soft model. In summary, the rigid-flexible model can greatly improve the simulation speed of the gear pair model.

5. Summary

(1) Based on the MFBD technology, a method for establishing a multi-flexible gear pair model using Creo, Hypermesh, and RecurDyn was constructed, and the accuracy of the model was verified.

(2) The frequency-domain variation law and the simulation speed of the rigid-flexible and flexible -flexible gear pair models are compared and analyzed. The results show that the rigid-flexible model has certain advantages in the simulation. The simulation process and results are the rigid-flexible coupling of the complex gear train. The establishment of the model provides reference and basis.

References

[1]. Hailong Gao, Xiao Wu, Zhenhua Li, et al. Research on Multi-body Dynamics Simulation of Flexible Gears. Lifting transport machinery. Vol. 42 (2009) No. 12, p. 78-82.

[2]. Yoo W S,Kim S S,Park T W, et al. Multi-body Dynamics Research in Korea. JSME .Vol. 46 (2003) No. 2, p. 449-458.

[3]. Chiyu Hao, Guangbin Feng, Pengcheng Yan, et al. Rigid-flexible Coupling Modeling and Simulation Analysis of Ramming Machine Based on MFBD. Vol. 35 (2016) No. 15, p. 161-167.

[4]. Yi Liu. The Application and Improvement of Recurdyn Multibody Dynamics Simulation. Electronic Industry Press, 2013, p. 9-10.

[5]. Yuankang Di. Application of Hypermesh in Force Analysis of Gears. Mechanical Engineering and Automation. Vol. 42 (2012) No. 6, p. 166-169.

[6]. Zhanguo Li, Yunhe Zhang, Yichen Shi, et al. Dynamic Simulation Analysis of Automobile Multi-wedge Belt Based on MFBD. Mechanical Transmission.Vol.37 (2012) No. 8, p. 34-36.

[7]. Xingguo Ma, Wei Yang, Xiaomei You, et al. Multi-body Dynamic Analysis of Rigid-flexible Coupled Planetary Gears. Chinese Journal of Construction Machinery.Vol.7 (2012) No.2, p. 146-151.